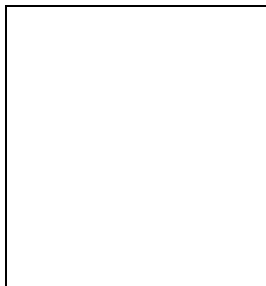


Gauge dilution in leptogenesis

N. Cosme

*Service de Physique Théorique, CP225
Université Libre de Bruxelles,
Bld du Triomphe, 1050 Brussels, Belgium.*



We discuss leptogenesis in its natural context, i.e. gauge unification, by including in the analysis the effects of the gauge sector associated to the Majorana neutrinos. It results in stricter bounds on the minimal Majorana mass, depending on the gauge bosons mass, but also prevents to deduce any lower limit on the Yukawa couplings since thermal and re-heating scenarios are now indistinguishable.

1 Introduction

The baryogenesis through leptogenesis scenario is a very appealing one in order to account for the observed baryon asymmetry in the universe.

In this scenario, heavy Majorana neutrinos linked to light left-handed neutrinos via Yukawa couplings decay namely through channels violating both lepton number and CP, once the temperature of the universe drops below the Majorana scale. These Majorana neutrinos decay out of equilibrium mainly according to the weakness of their Yukawa couplings.

As a consequence, all Sakharov conditions may be fulfilled to create a non zero lepton asymmetry.

Furthermore, around the electroweak phase transition, non-perturbative $B - L$ conserving interactions, as exemplified by sphalerons, convert this initial lepton number partially to baryons giving thus rise to the observed baryon asymmetry.

We will discuss this issue further in relation with the neutrino mass parameters and with special emphasis on the effect of gauge couplings to Majorana neutrinos from the unification.¹,² These gauge couplings are for us an integral part of the extension to right-handed neutrinos but are usually (and unjustifiably) neglected.

A simple model of leptogenesis is the standard model together with a generation of right-handed neutrinos having a Majorana mass term. We list here the relevant lepton Yukawa couplings:

$$\bar{l}_L \phi \lambda_l e_R + \bar{l}_L \tilde{\phi} \lambda_\nu N + \frac{1}{2} \bar{N}^c M N + h.c., \quad (1)$$

where $l_L = (\nu_L, e_L)^t$, ϕ is the standard model scalar doublet and N the Majorana neutrinos with mass matrix M .

In addition to the above interactions, the unification is obviously accompanied by gauge bosons coupled to Majorana neutrinos. Irrespective of the details of the symmetry breaking, we can expect that the induced Majorana mass will be related to the masses of some gauge bosons by the breaking mechanism.

As a result, these degrees of freedom would be relevant for the leptogenesis process and therefore a full description should include the part of the gauge sector linked to right-handed neutrinos.

At the very least, one should consider right-handed charged and neutral currents coupled to particles as W_R^\pm and a Z' from an $SU(2)_R$ gauge symmetry.

While an explicit passage through the stage $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ in the actual breaking of the unification structure is not mandatory, the inclusion of the above-mentioned particles is logical and characteristic of the actual Majorana neutrino gauge couplings.

The inclusion of these gauge couplings in the description of leptogenesis has consequences at different levels:

1. it dilutes the CP asymmetry by new CP conserving decay channels;
2. it reduces the Majorana decoupling from the thermal bath through additional diffusions mediated by gauge bosons;
3. it favors the Majorana production if the Majorana population have to be establish, e.g. in a re-heating scenario.

2 CP asymmetry

The CP asymmetry in the decays of heavy Majorana neutrinos arises in the channel ($N_i \rightarrow l_L \phi + N_i \rightarrow \bar{l}_L \phi^\dagger$) at one loop order from the interference of the tree level amplitude with the vertex and self energy corrections:

$$\epsilon_i^\phi = \frac{\Gamma(N_i \rightarrow l \phi) - \Gamma(N_i \rightarrow \bar{l} \phi^\dagger)}{\Gamma(N_i \rightarrow l \phi) + \Gamma(N_i \rightarrow \bar{l} \phi^\dagger)}. \quad (2)$$

If we assume hierarchical Majorana masses : $M_1 \ll M_2 \ll M_3$, the only N_1 decay is relevant regarding the final lepton asymmetry. It is then possible to derive model independent upper bounds on the CP asymmetry which will then be used as a necessary condition for successful leptogenesis. For instance, Davidson and Ibarra deduce the following upper bound³:

$$|\epsilon_1^\phi| \leq \epsilon_{DI}^\phi = \frac{3}{16\pi} \frac{M_1}{v^2} (m_3 - m_1). \quad (3)$$

This bound has however been further improved in⁴ that we will use in the following.

Including gauge interactions for the Majorana allows additional decay channels which are CP conserving.

Two cases can be distinguished. First, when $M_1 > M_{W_R}$, that is the W_R gauge boson is lighter than all Majorana neutrinos, the additional decay channels mostly occur in a two body

decay into an on-shell W_R . This possibility implies a quite large partial decay width which dilutes excessively the CP asymmetry leading to an unsuccessful leptogenesis scenario, and is therefore excluded.¹ In the second case, for $M_1 < M_{W_R}$, the dominant additional channels are three body decays. In this second case, we keep the possibility of a successful leptogenesis. We will not consider the $M_1 \simeq M_{W_R}$ degenerate case here.

3 Diffusion Reactions

Beside the decay processes leading to the generation of the lepton asymmetry, we also have to consider the reactions constituted by all the possible diffusions of Majorana neutrinos and leptons.

These diffusions keep the Majorana neutrinos coupled to the other particles in the thermal bath and prevent for the departure from equilibrium. In brief, successful leptogenesis relies on the strength of the different reactions. More accurately, the dimensionless quantity involved in the evolution equations is the ratio γ/s to H , i.e. the ratio of the interaction rate per unit of time to the universe expansion rate:^a

$$H(z) \propto \frac{M_1^2}{z^2 M_{Pl}}; \quad s(z) \propto \frac{M_1^3}{z^3}, \quad \gamma(z) \propto \frac{M_1^4}{z} \int dx \hat{\sigma}(x) \sqrt{x} K_2(x\sqrt{z}). \quad (4)$$

The couplings in the scalar sector give rise to $\Delta L = 1$ (e.g. $N_1 l_L \rightarrow \bar{t}_R Q_L$) and $\Delta L = 2$ (e.g. $l_L l_L \rightarrow \phi\phi$) diffusion reactions. The former are involved in the thermal coupling of Majorana neutrinos while the latter induce a wash out of the lepton asymmetry as they are in equilibrium. The dependence in the neutrino mass parameters is as follows:

$$\frac{1}{H(M_1)s} \gamma_{\Delta L=1} \propto \tilde{m}_1 \frac{M_{Pl} m_t^2}{v^4}, \quad \frac{1}{H(M_1)s} \gamma_{\Delta L=2} \propto \tilde{m}_1^2 M_1 \frac{M_{Pl}}{v^4}, \quad (5)$$

where we restrict to the only N_1 Majorana in the propagator for the second rate. We introduced here the important parameters $\tilde{m}_1 = \frac{v^2 (\lambda_\nu \lambda_\nu^\dagger)_{11}}{M_1}$. Since it mimics a see-saw type formula, \tilde{m}_1 provides an effective light neutrino mass relevant in the estimate of the decay width and of the other Majorana neutrino interactions.

Once we include the Majorana gauge interactions, we observe an additional behavior along the Majorana mass parameter. Indeed, the strength of W_R and Z' mediated interactions (e.g. $N_1 e_R \rightarrow \bar{u}_R d_R$, $N_1 N_1 \rightarrow e_R^- e_R^+$) fall when M_1 increases.⁵

$$\frac{1}{H(M_1)s} (\gamma_{W_R}, \gamma_{Z'}) \propto \frac{1}{M_1} M_{Pl}. \quad (6)$$

The complete dynamics of the lepton number creation process may be conveniently synthesized in a dimensionless quantity called the efficiency which corresponds roughly to the percentage of lepton number actually created in the process with respect to the maximum lepton number possible.^{6,7,8} We present in Figure 1 the efficiency of leptogenesis in the (\tilde{m}_1, M_1) plane in the case where the gauge interactions for Majorana neutrinos are neglected and for given W_R to Majorana mass squared ratios $a_w = (M_{W_R}/M_1)^2$.

Different behaviors are revealed. In the minimal case (corresponding to the artificial case $a_w \rightarrow \infty$), two main effects are seen : First, for low \tilde{m}_1 , the Majorana neutrino decays strongly out of equilibrium but in the re-heating scenario (zero initial Majorana abundance) the Yukawa couplings limit the Majorana production. For larger \tilde{m}_1 , the Majorana decays almost in equilibrium resulting in less lepton number but the Majorana production is then no more a problem.

^awhere $\hat{\sigma}$ is the reduced cross section defined as $\hat{\sigma}(aI \rightarrow J)(s) = (8/s)[(p_a \cdot p_I)^2 - m_a^2 m_I^2] \sigma(s)$, $z = M_1/T$, $x = s/M_1^2$.

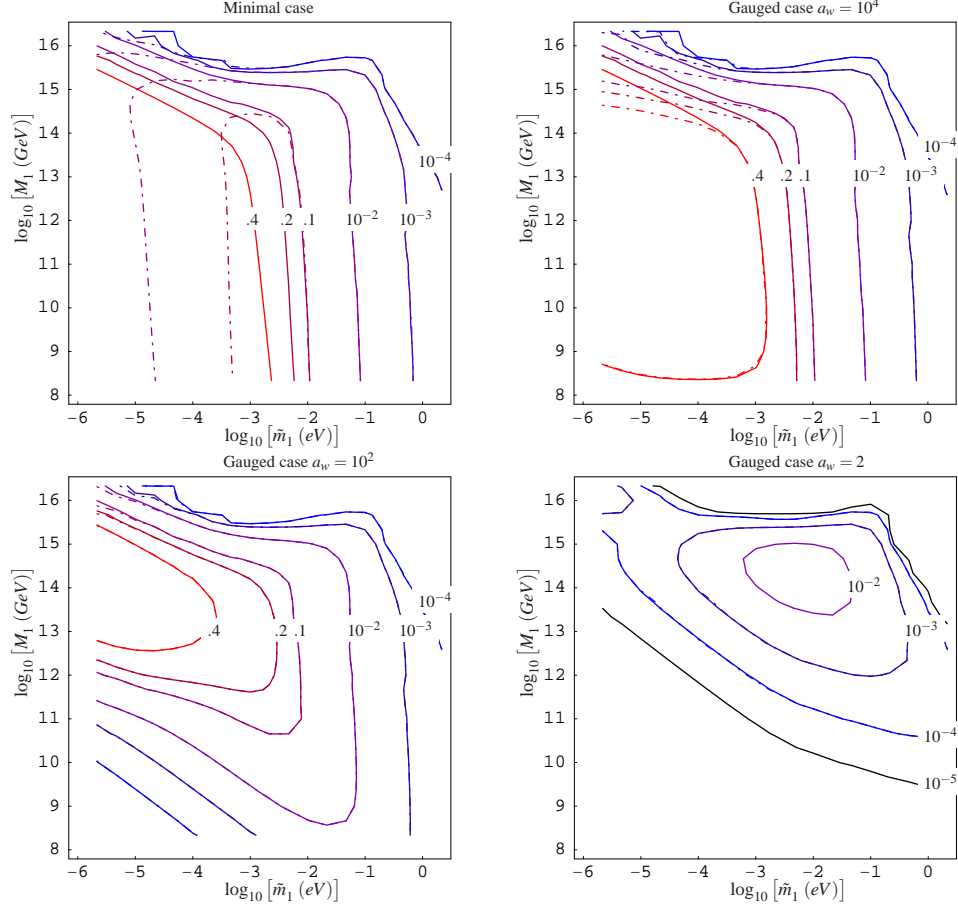


Figure 1: Efficiency of leptogenesis for the minimal case $a_w \rightarrow \infty$ and the extended case to a minimal right-handed gauge sector for $a_w = M_{WR}^2/M_1^2 = 10^4, 10^2, 2$. The continuous line is the efficiency for a thermal initial Majorana abundance (thermal scenario) while the dashed-dotted line is for a zero initial Majorana abundance (re-heating scenario).

Secondly, for large M_1 , the produced lepton number is washed out by $\Delta L = 2$ diffusions mediated by Majorana neutrinos.

As we turn on the gauge interactions, this description is modified by two points:

The creation of heavy Majorana neutrinos is enhanced by the gauge interactions so that there is far less dependency according to the initial condition, even for a sizable a_w ratio.

The second consequence is a drastic reduction of leptogenesis efficiency for low Majorana mass which increases dramatically for low a_w ratio. This comes from both delayed or impeded decoupling of Majorana neutrinos through additional diffusions and decay channels.

Both effects impact the conclusions drawn for the neutrino mass parameters.

4 Baryon asymmetry and neutrino mass

Using the ability of leptogenesis to account for the observed baryon number, we can provide constraints on the neutrino mass parameters. These bounds are indeed useful for the understanding of neutrino mass patterns and hence physics at energy well above the standard model.

Therefore the baryon to photon ratio expected from leptogenesis is expressed in terms of the sphaleron conversion rates⁹ and the leptogenesis efficiency (η_{eff}):

$$\frac{n_B}{n_\gamma} \simeq \frac{s}{n_\gamma} C_{sph} |Y_L| \simeq \frac{196}{79} \epsilon_1^\phi Y_{N_1}^{eq}(init.) \eta_{eff}, \quad (7)$$

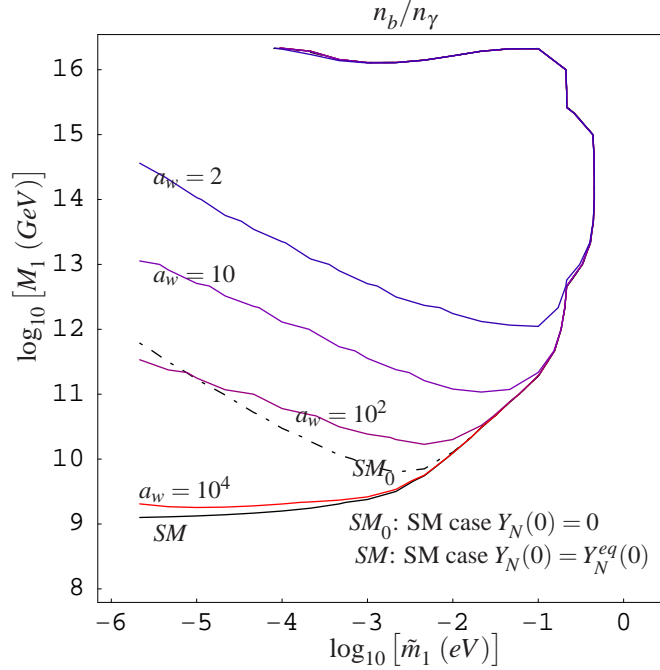


Figure 2: Limits on the baryon to photon ratio in an extended model to a minimal right-handed gauge sector with $a_w = M_{W_R}^2/M_1^2 = 10^4, 10^2, 10, 2$, from bottom to top (red to blue). The minimal SM case is also shown in black: the continuous line is for a thermal initial Majorana abundance while the dashed-dotted line is for a zero initial Majorana abundance. The matter asymmetry is higher than the WMAP value in the region bounded by the curves.

where we assume that the bound on the CP asymmetry derived in⁴ is saturated. Figure 2 shows the iso- n_B/n_γ curves in the (\tilde{m}_1, M_1) plane obtained for different a_w ratios, assuming the central value of baryon asymmetry from WMAP: $10 \frac{n_B}{n_\gamma} = (6.1_{-0.2}^{+0.3}) \times 10^{-10}$. The baryon asymmetry is higher than this value in regions bounded by the curves.

As already mentioned, the re-heating scenario is almost indistinguishable with the gauge inclusion from the thermal scenario. As a consequence, the full description of leptogenesis prevents to deduce any lower limit on the effective neutrino mass \tilde{m}_1 as occurs in an incomplete analysis. For comparison, the minimal (non-gauged Majorana) model curve for an initial thermal Majorana abundance coincides in practice with the curve for $a_w = 10^6$ (the latter irrespective of the thermal or re-heating scenario).

Finally, successful leptogenesis requires a large enough Majorana mass. The gauge inclusion moreover teaches us that it evolves with the Majorana to W_R mass ratio.

5 Conclusion

We considered the description of leptogenesis in its natural context, i.e. gauge unification, by including in the analysis the gauge bosons coupled to the Majorana neutrinos.

The main results are:

1. the W_R mass has to be larger than the Majorana mass M_1 in order to get a successful leptogenesis scenario.
2. the minimal allowed Majorana mass increases depending on the associated gauge boson masses.
3. the re-heating scenario is almost indistinguishable in our framework from the case of a

thermal scenario, resulting in a broader window for Yukawa couplings in the case of zero initial Majorana abundance (re-heating scenario).

Acknowledgments

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